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RENEW v3.2 User's Manual, Maintenance Estimation Simulation for Space Station Freedom Program

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RENEW Version 3.2 User's Manual
Maintenance Estimation Simulation Model
for Space Station Freedom Program
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FOREWORD

Lewis Research Center (LeRC) engineers developed the RENEW simulation software in response to the need for greater fidelity in modeling the 30 year mission and resupply environment for Space Station Freedom. While the software is focused on resupply of on-orbit replaceable units of the Space Station Freedom it uses modeling techniques that apply to other mission scenarios.

ACKNOWLEDGEMENTS

The RENEW software has been a collaborative effort between LeRC and SAIC (Scientific Applications International Corporation) engineers. The modeling techniques were developed and the software evaluated with the assistance of Edward Zampino and David Hoffman from NASA Lewis Research Center, and W. James Dorcey from SAIC.

1.0 INTRODUCTION

RENEW is a maintenance event estimation simulation program developed in support of the Space Station Freedom Program (SSFP). This simulation uses reliability and maintainability (R&M) and logistics data to estimate both average and time dependent maintenance demands. The simulation uses Monte Carlo techniques to generate failure and repair times as a function of the R&M and logistics parameters. The estimates are generated for a single type of orbital replacement unit (ORU).

The RENEW simulation gives better estimates of performance over a given time period than steady-state average calculations since RENEW uses a time-dependent approach and depicts more factors affecting ORU failure and repair. RENEW gives both average and time dependent demand values. Graphs of failures over the mission period and yearly failure occurrences are generated. The average demand rate for the ORU over the mission period is also calculated. While RENEW displays the results in graphs, the results are also available in data tables.

2.0 PROGRAM OVERVIEW

RENEW is a compiled program written with Microsoft QuickBASIC. It runs on an IBM-286/386 system with 640K memory, CGA or VGA graphics card, and DOS 3.0 or higher operating system. The program is a single file "RENEW32.EXE". Data files are produced by the program for storage of input and output data. The RENEW program must be on the same DOS drive as the data files. See Appendix B for more information regarding installation and files.

The process of using RENEW starts with keyboard entry of the R&M and operational data. Once entered, the data may be saved in a data file for later retrieval. The parameters may be viewed and changed after entry using RENEW. The simulation program runs the number of Monte Carlo simulations requested by the operator. Plots and tables of the results can be viewed on the screen or sent to a printer. The results of the simulation are saved along with the input data. Help is provided with each menu and data entry screen.

In this manual, *menu titles* and *screens* are shown in italics. Menu selection keys are shown enclosed by brackets [] followed by the menu name in brackets {}. Selections are made by typing the menu selection key followed by the [Enter] key on the keyboard. Typing only the [Enter] key at the "Selection" prompt returns the previous menu.

3.0   USING RENEW

3.1   RENEW Selections

There are two forms of the *Main Menu* depending on whether data has been entered or retrieved. The first screen displayed on executing RENEW32 from DOS does not have selections to [L]ist/change data, view Simulation [R]esults or [E]xecute the simulation. Once data is input, these selections are added to the menu.

The Data and Files selections provide a means for [K]eyboard Data Input or [F]ile Data Input. The data and results may be [S]aved after entry or simulation execution. A special [B]atch and Summary files menu allows processing of multiple data files. Text files, including all the RENEW input data and output reports, may be viewed with the File Viewer [FV]. With the [F] and [FV] selections, files can only be selected from the current default DOS directory. The default can be changed using [CD] Change Directory. The current default DOS directory is displayed on the screen below this selection.

```
Renew Simulation - V3.2 - Main Menu

DATA AND FILES
*  [K]eyboard Data Input              [B]atch and Summary files
*  [F]ile Data Input                  [FV] File Viewer
   [S]ave Input Data and Results      [CD] Change Directory
                                           {D:\RENEW}
DATA VALUES & FUNCTIONS
*  [C]onstants                        [L]ist/Change Parameter Values
*  Resource [V]alues                  [D]isplay Functions


SIMULATION RESULTS
   [P]lot Histogram                   [A]verage Resupply and Maintenance
   [R]esulting Statistics             [Y]early Event Estimates


[H]elp                                [E]xecute Simulation

[Q]uit

* these selections affect simulation results

Selection:
```

Main Menu

3.2 Entry of R&M Data

The original R&M data for an ORU must be supplied through the keyboard by selecting [K]eyboard input *{Main Menu}*. Data validity checks are made as the data is entered. If an entered value is incorrect (e.g. MTBF < 0), the operator is prompted with a description of valid values for the parameter. Upon typing only the <Enter> key a help prompt is displayed and the data may then be entered using this as guidance. The prompted data items are listed and described in Appendix A. Once data has been entered, it can be saved and later retrieved for modification or re-execution by the simulation (Figure 1).

The [L]ist/Change Data selection *{Main Menu}* can be used to view or change data values. This allows verification and editing of entries.

```
Renewal Simulation - V3.2 - List/Change Parameters          Run Date: 10-27-1992
[NAM]   ORU Name                   ORU_1           ORU   Start
[TYP]   ORU Type                   EL - Electrical  No.   Time
        No. of ORUs                6                1     0
[ST]    Start times                                2     0
[EP]    Prob. of Early Failure     .05             3     1.5
[EL]    Early Mean Life            1 year          4     1.5
[ES]    Early Shape                .4              5     4
[MT]    MTBF Type                  Constant        6     4
[MTBF]  MTBF                       35 years
[DC]    Duty Cycle                 1
[MMD]   MTBF-Micrometeroid/Debris  1E+29 years
[WT]    Wearout mean life type     Constant
[WL]    Wearout Weibull Mean Life  15 years
[WF]    Failure Free Period        0 years
[WS]    Wearout Weibull Shape      10
[RD]    Replacement Downtime       0 years
[TIM]   Mission Time               30 years
[ND]    No. of Divisions/year      1
[NS]    Number of Simulations      1000
[RR]    Replacement Ratio          .8
[K]     K-Factor                   1.63
Enter abbreviation of parameter to change
    or <Enter> for no change:
```

List/Change Parameters Menu

While the major set of R&M data is entered through the [K]eyboard selection *{Main Menu}*, the [C]onstants and Resource [V]alues *{Main Menu}* choices allow entry of other data that affect the results.

The *Constants Menu* allows setting the default values for various types of K-factors used to modify the Mean Time Between Failures (MTBF) and mean life parameters and the replacement ratio. All of the constants have a default of 1 which effectively removes these from the simulation. Changing these values will have an effect on the resulting base number of failures. If any changes are made, the results will be erased and the simulation will have to be re-run. The default K-Factor is assigned to an ORU on keyboard entry according to the ORU type indicated. The defaulted K-factor value can be changed with the K-Factor [K] selection on the *List/Change Parameters* Menu. All of the factors can be set to default values with the choices at the bottom of the screen. The Replacement Ratio [RR] may also be set from this menu. Once set, these values will be applied to each data set entered using the [K]eyboard selection *{Main Menu}*.

```
Renewal Simulation - V3.2 - Constants

Reliability Growth:
  1st failure (E1)                    3.3
  2nd failure (E2)                    2.17
  3 and more  (E3)                    .6666667

K-Factors:
  Mechanical (Kme)                    1
  Structural (Kst)                    1
  Structural-Mechanical (Ksm)         1
  Electrical (Kel)                    1
  Electro-Mechanical (Kem)            1
  Electronic (Kec)                    1

Replacement Ratio                     .8

Set all factors to 1.0   (R1)
Set all K-factors to 2.0   (R2)
Set all factors to EMST values (EMST) - Jan 91 Draft Report
Set all factors to EMTT values (EMTT)
Set all factors for Work Package 4 (WP4)

Enter factor abbreviation or <Enter> to continue:
```

Constants Menu

The *Resource Values* menu contains mass, Mean Time To Repair (MTTR) and crew parameters. The MTTR parameter will affect the simulation through the amount of downtime. The mass and crew values are only used in calculations based on the final results and are not used during the simulation.

If any changes are made to the value of the parameters in the *List/Change Parameters*, *Constants*, or *Resource Values* menus, the existing results of the simulation are erased. If this were not done, the results would not match the input data. The user is cautioned to save the results before changing data values.

```
Renewal Simulation - V3.2 - Resource Values

For ORU:   ORU_1

ORU Mass (M)                        30 pounds

Mean Time To Repair (MTTR):
    EVA        (E)                  .6 hours
    Robotic    (R)                  0 hours
    IVA        (I)                  0 hours

Number of Crew:
    EVA        (EC)                 1
    IVA/Robotic Crew (IC)           0


[H]elp

NOTE: * * Changing resource values will erase current results * *

Enter abbreviation of parameter to change
    or <Enter> for no change:
```

Resource Values Menu

Some of the parameters in the previous data entry menus may be removed from the simulation by using appropriate values. This allows execution of the simulation when not all of these parameters are known or needed. Suggestions are shown below:

Parameter	To Remove from Simulation
Early Failures	Set early failure probability (EP) to 0
K-factors	Set to 1
MTBF	Set to 1E+29
MTBF for Micrometeroid/Debris	Set to 1E+29
Reliability growth factors	Set to 1
Wearout	Set mean life to a couple of multiples of the mission time, Set shape to 20

For example, if an ORU is only modeled with a wearout distribution, the Early Failure Probability parameter, [EP], should be set to zero and the MTBF should be set to 1E+29. This will remove the influence of these parameters on the simulation.

The [D]isplay Functions menu {Main Menu} provides plots of the [R]eliability, [H]azard, and [P]robability density functions for the composite distribution (Figure 2). These curves will give an indication of the shape of the distributions that will be used in the simulation with the given input parameter values. This selection is not available when variable MTBF or variable mean life is used.

3.3 Executing the Simulation

The simulation may be [E]xecuted *{Main Menu}* once data has been either entered by keyboard or retrieved from a data file. The *List/Change Parameters* screen is displayed for information with the current simulation number displayed at the bottom of the screen during execution. Typing any key will cause the simulation to stop and return to the *Main Menu* with input data preserved but no results. The results are not saved to a disk file until the user selects [S]ave Input Data and Results *{Main Menu}*.

3.4 Simulation Results

Choices to view the results of the simulation are presented on the *Main Menu* once the simulation has completed execution. The results are available by topic in both graphical and report format. Graphs can be printed by typing a "*" to "Print" when the graph is displayed on the screen. The only graphics printer format supported is an HP laserjet. The resolution is defaulted to 75 dots per inch but can be changed to 150 dots per inch by typing [*] *{Main Menu}*. Other results and files are written in ASCII and contain no embedded printer codes. A set of data and results files under the base file name "TEST" are contained on the distribution diskette with the RENEW software. Data and results in the .RD3 file can easily be imported into spreadsheets for further analysis.

3.4.1 Failure Event Histogram

Choosing [P]lot Histogram *{Main Menu}* will display a histogram of the average number of failure events per year (Figure 3). The initial histogram displays the total events curve along with a second curve depicting the events generated by the highest contributing factor (early, random or wearout). The curves for [E]arly, [R]andom, or [W]earout will be displayed by typing the first letter shown *{Plot Histogram}*. The percentages of the total caused by each type of failure event (early, random, wearout) are shown.

3.4.2 Resulting Statistics

Choosing [R]esulting Statistics *{Main Menu}* will give a summary page followed by a number of pages of raw simulation results. The summary page gives:

Total Mission Results
- Average number of Failure Events per total mission
- Standard deviation of average failure events due to the simulation
- Mean Time Between Failure Events (MTBFE) over the mission
- Early, Random, Wearout Percentages based on the number of failure events
- Average No. of Maintenance Actions
- Mean Time Between Maintenance (MTBM) over the mission
- Number of Replacements
- Mean Time Between Replacement (MTBR) over the mission

Yearly Results
- Maximum Failure Events/year
- Year of maximum Failure Event/year occurrence
- Average Failure Events/year

Availability
- Total Available Operating Time for all ORUs
- Total ORU Uptime and Downtime
- ORU Availability based on uptime and downtime
- ORU MTBFE based on uptime and downtime

The [I]nformation selection *{Resulting Statistics}* should be used to view an interpretation of this data on three *Results Information* screens.

```
Renewal Simulation - V3.2 - Results

ORU:  ORU_1        Datafile name: ORU1.RD3          Run Date: 10-27-1992

TOTAL MISSION RESULTS
  Failure Events:                17.911            MTBFE: 1.674948 years
     6.2% Early           (Std Dev= 2.227564 )
    68.0% Random
    25.8% Wearout
  No. of Maintenance Actions:    17.911
  No. of Replacements:           14.353

YEARLY RESULTS
  Maximum Failure Events/year:   .861 occurs at 5 years
  Average Failure Events/year:   .5970333

AVAILABILITY
  Total Available Operating Time:  169          ORU-years
  Total ORU Uptime:                168.9988     ORU-years
  Total ORU Downtime:              1.226781E-03 ORU-years
  ORU Availability:                0.999993
  ORU MTBFE:                       9.435474        years

[I]nformation or <Enter> to continue: ?
```

Resulting Statistics Screen

The raw simulation data follows this menu in three tables before returning to the *Main Menu*:

> Simulation Event Data
> -   This data is used to generate the [P]lot Histogram *{Main Menu}*.
> -   The columns list the time bin with the total, early, random, and wearout failure events per bin.
> Yearly Failure Event Data
> -   This data is used to generate the plots in the *Yearly Event Estimates* menu.
> -   The listing shows the number of simulations where a particular number of failures occurred (e.g. 0 failures occurred in 960 out of a 1000 simulations with 1 failure in 40 of the simulations).
> Yearly Replacement Event Data
> -   This data is used to generate the plots in the *Yearly Event Estimates* menu.
> -   The listing shows the number of mission simulations where a particular number of replacements occurred.

The replacement event data will vary from the failure event data when the replacement ratio *{List/Change Parameters Menu & Constants Menu}* is not 1.

3.4.3 Average Resupply and Maintenance

The [A]verage Resupply and Maintenance *{Main Menu}* selection gives a listing of averages over the mission and the simulation parameter values used to base these calculations.

Averages Per Year Over the Entire Mission

-   Annual Resupply Mass calculated from the replacement events per year, and ORU mass.
-   Mean Maintenance Time per Year for External Vehicular Activity (EVA), Internal Vehicular Activity (IVA), and Robotic from the maintenance events per year and the Mean Time To Repair (MTTR).
-   80% Probability of Sufficiency (POS) Replacement Quantity based on the average replacement events per year and standard deviation of failure events from the simulation.

Average events per year, starting with years 3 and 4 through mission end

-   These figures are calculated from a sum of the total simulation event data over the years of interest. This time segment was created to give an average event value in the operation phase after the 3 to 4 year SSF assembly phase.

```
Renewal Simulation - V3.2 - Average Resupply and Maintenance


Averages Per Year Over a 30 year Mission:
   Annual Resupply Mass:            14.3 pounds

   Mean Maintenance Time/year:      EVA          0.4 hours
                                    Robotic      0.0 hours
                                    IVA          0.0 hours


   80% POS replacements/year:       .666667

Averages
For 3 through 30 years:            .631 events/year
For 4 through 30 years:            .6340769 events/year

Based on:      .5970333 average maintenance events per year
               Replacement ratio of .8
               .4776267 replacement events per year
               .6 hour EVA time of 1 crewmember
               0 hour Robotic time of 0 crewmembers
               0 hour IVA time of 0 crewmembers
               30 pound ORU mass
```

Average Resupply and Maintenance

3.4.4 Yearly Event Estimates
The [Y]early Event Estimate {Main Menu} selection gives a menu of selections that provide statistics and curves for individual years during the mission. Selections from the Yearly Event Estimates Menu are:

Type of Data
- Selection of Failure Events [FE] or Replacement Events [RE] determines which set of data will be used in the yearly summaries.

Overall and Yearly Data
- The [E]vents in each mission shows a table of the total number of events with a summary of Minimum, Maximum, Average and Standard Deviation.
- The [O]ccurrence of Events and Cumulative Frequency Distribution gives a table of the number of events, number of occurrences, and cumulative frequency distribution (CFD) tables.
- The [H]istogram of Event Occurrences & CFD (Figure 4) provides a plot of the data in the previous tables.

Probability of Needing a Replacement over the Mission Time
- The [P]OS to number of events will calculate the number of events that has at least the POS specified.
- The [N]umber of events to POS will give the Probability Of Sufficiency for a given number of events.

[C]umulative min/max estimates
- For a given round up fraction, the minimum, average and maximum events are tabulated.
- Cumulative data is calculated from the event histogram.

[A]ssistance
- A help screen is provided for guidance.

```
Renewal Simulation - V3.2 - Yearly Event Estimates


Type of Data:  (Currently  FE-failures)
   Failure Events           (FE)
   Replacement Events       (RE)

Overall and Yearly Data:
   [E]vents in each mission
   [O]ccurrence of Events and Cumulative Frequency Distribution (CFD)
   [H]istogram of Event Occurrences & CFD

   [P]OS to number of failure events
   [N]umber of failure events to POS

   [C]umulative min/max estimates

[A]ssistance

Selection:
```

Yearly Event Estimates Menu

```
Renewal Simulation - V3.2 - Occurrence of failure Events -  30 year Mission

No. of                               Cumulative
failure          No. of              failure
Events           Occurrences         Probability
------           -----------         -----------
  11             2                      0.0020
  12             2                      0.0040
  13             13                     0.0170
  14             42                     0.0590
  15             66                     0.1250
  16             141                    0.2660
  17             173                    0.4390
  18             185                    0.6240
  19             157                    0.7810
  20             90                     0.8710
  21             65                     0.9360
  22             39                     0.9750
  23             17                     0.9920
  24             7                      0.9990
  25             0                      0.9990
  26             1                      1.0000
                 -----
                 1000
```

Occurrence of failure Events Screen

3.5   Batch Files
      This option is selected with the [B]atch & Summary File *{Main Menu}* selection.
      A list of ORU files may be submitted for consecutive execution using a RENEW
      batch file. This batch file contains the file names of individual ORU data files.
      The batch file is an ASCII text file and is given an .RB3 extension. The *Batch &*
      Summary File menu provides selections for creation, listing and use of batch
      files with the following commands:

      [C]reate
            This selection is used to create a batch file (.RB3). The batch file may also
            be created or edited with a text processor.
      [L]ist Contents
            The presence of the individual ORU data files (.RD3) listed in the batch file
            (.RB3) is checked. It is recommended that this selection be used prior to a
            batch run to ensure that all of the ORU data files are present.
      [R]un
            The different ORUs are run in sequence with the results stored in the ORU
            data files (.RD3) for later retrieval.
      [S]ummary of data & results (.RS3)
            Selected results from the ORU files are extracted and combined in a listing.

      [SE]-03 Format
            Another selection of results from ORU files, printed in a 120 character wide
            text file. The file name has a .RE3 extension. This can be viewed with the
            [FV] *{Main Menu}* selection. (Note: SE-03 refers to a data requirement
            report for SSFP).
      [B]lock Data Change
            The value of a single R&M data element is modified in all files listed in the
            batch file. This is done by selecting a [B]atch file *{Block Data Change}* and
            then the data [E]lement to change *{Block Data Change}* and the new value.
            The files will be modified on selecting [C]hange element value in files
            {Block Data Change}.

3.6   Saving & Retrieving Data Files
      Using [S]ave Input Data and Results *{Main Menu}* will save the data and results
      to a file. The ORU name supplied in the data file is used to create the DOS file
      name with a .RD3 file extension. The user may change the name of the file
      before it is saved.

      All files are saved and retrieved to/from the default DOS directory. This
      directory can be changed using Change Directory [CD] *{Main Menu}*.

```
Renewal Simulation - V3.2 - Batch & Summary Files


Batch Files (.RB3):
  [C]reate Batch File
  [L]ist Batch File Contents
  [B]lock Data Change
  [R]un Batch

Summary Files:
  [S]ummary of Data & Results (.RS3)
  [V]iew Summary File Contents

  [SE] - 03 Format File (.RE3)

[H]elp

Selection:
```

Batch and Summary Files Menu

[F]ile Data Input {Main Menu} can be used to locate and load data files in the default directory on the drive.

All of the RENEW results files are in text format and can be viewed using the File Viewer [FV] {Main Menu}.

4.0   RENEW MODEL BACKGROUND

4.1   Maintenance Interval Estimation

Preliminary maintenance analyses generally use the steady state average of the failure interval, represented by the MTBF, to calculate the number of maintenance events. Each failure is assumed to generate a maintenance action. Both Logistics [Blanchard, p.52] and Reliability use this approach. The number of failures over a given mission time is:

1) $n(t) = N * (t / MTBF) = N \lambda t$

where $n(t)$ = Number of failures
         N = Number of items
         λ = Failure rate
         t = Mission time

Maintenance repair hours and resupply quantity are then calculated from the number of failures and the Mean Time To Repair (MTTR).

2)   Maintenance Hours = MTTR * n(t)

3)   Resupply Quantity = n(t)

This approach is a good estimator under the following constraints:

o   Items exhibit only random failures
o   There is no internal redundancy
o   Mission times are long with respect to the MTBF
o   Repair is made with no downtime
o   Spares are always available
o   Every failure requires a spare
o   The MTTR is the same for every failure of a specific ORU

4.2   Renewal Approach

Steady state methods are appropriate when the mission time is many multiples of the basic Mean Time To Failure (MTTF) [Lewis, p.109]. Calculations based on steady-state averages will always over estimate the number of maintenance events by predicting extra events that do not occur [Barlow/Proschan, p. 53]. This error is caused by two factors:

Fractional Carryover from End Effects
> Averaging methods estimate the number of events from the number of MTBF intervals that occur over the mission life. Fractional events are counted as part of the average and increase the number of events. When many multiples of the MTBF occur during the mission time, the error from a fractional event is not significant in the total count. When the mission time approaches infinity the results reduce to the steady state [Lloyd/Lipow, p.275].

MTBF and Wearout Interactions
> The random and wearout failure modes are not independent. A random failure will preclude a wearout failure. The replacement ORU is thus "brand new" with its wearout life clock reset to zero. This is not accounted by either a a series R(t) function or a steady-state average.

The basic renewal theory equation directly calculates the number of renewals, $M(t)$ [Barlow/Proschan, p.50]:

4) $\quad M(t) = F(t) + \sum_{k=1}^{\infty} {_0}\int^t F^{(k)}(t-x)\, dF(x)$

$\quad\quad$ where, $\quad\quad F(t) = 1 - R(t)$
$\quad\quad\quad\quad\quad\quad\quad\quad F^{(k)} = $ kth convolution of $F(t)$

Solution of equation 4) requires use of Laplace transforms. As an alternative to this, a computer-based simulation can be used. Interactions of the failure events with the mission time can be evaluated as they occur in the simulation. A simulation also allows other time varying factors to be included thus increasing the fidelity of the results, such as:

o Staged deployment or assembly sequence
o Early life failures
o Technology improvement
o Shuttle resupply intervals
o Maintenance backlogs
o Grouping of repairs

A simulation allows collection of year by year estimates of maintenance events while considering other factors. It also gives a more realistic assessment of events for a given set of data.

RENEW was written to perform a computer simulation that accounts for these interactions. The maintenance demand for a single type of ORU is generated. Renewal effect, early, random and limited life distributions, and staged deployment are accounted in the simulation. A Mean Time Between Demand (MTBD) for maintenance and a time dependent maintenance demand curve is generated. The simulation uses the following type of data to arrive at these final metrics for a type of ORU:

ORU$\quad\quad\quad\quad\quad$ Quantity and Time of deployment
$\quad\quad\quad\quad\quad\quad\quad$ Early life probability and distribution
$\quad\quad\quad\quad\quad\quad\quad$ Random event MTBF
$\quad\quad\quad\quad\quad\quad\quad$ Wearout mean life and distribution
$\quad\quad\quad\quad\quad\quad\quad$ K-Factor and reliability growth factors
$\quad\quad\quad\quad\quad\quad\quad$ Replacement ratio

> ENVIRONMENT   Mission time
> Replacement Downtime
>
> SIMULATION   Number of trials
> Divisions per year

The primary product of RENEW is an average failure event time histogram derived from the simulation of maintenance events (Figure 3). The horizontal axis is the mission timeline and the vertical axis is the number of events. This failure histogram gives an estimate of the year by year demand. The MTBD for all ORUs and the Mean Time Between Maintenance (MTBM) for an individual ORU are obtained from the total number of events and downtime over the simulated mission time.

4.3   Failure Simulation

RENEW uses a Monte Carlo event stepped simulation. The event time generation uses a modified approach to account for the combination of the three major distributions (early, random and wearout). With competing risk models [Mann, p. 142], the reliability functions are multiplied:

5) $R_{oru} = R_{early} * R_{random} * R_{wearout}$

When this is used for all three distributions, the early life reliability (R_{early}) typically dominates the ORU reliability because it precludes any random or wearout failures. This model is, instead, used with the early failure distribution removed and applied to random and wearout events in a mixed distribution.

Early failures due to infant mortality, usually within about 12 months, will only occur on a percentage of the ORUs. To overcome the problem with equation 5) and more accurately depict expected behavior, a mixed distribution model [Mann, p. 138] is used to depict the early life failures. This model uses an early failure probability (EP) of occurrence. The simulation thus activates early failures with this probability. When no early failure occurs, a competing risk model is used for estimating only the random and wearout failure events. This modified approach is shown below:

6) $R_{oru} = \begin{cases} R_{early} & \text{with probability EP} \\ R_{random} * R_{wearout} & \text{with probability 1-EP} \end{cases}$

Time to failure intervals for ORUs are generated using algorithms derived from the reliability equation, R(t), for each failure distribution. R(t) is solved for time, t, with reliability, R(t), replaced by the random number. This generates a time to next failure that is governed by the distribution. The simulation steps in time from one failure of an ORU to the next. Appendix C lists the equations used for failure times with each failure distribution. See Figure 6 for use of these parameters in failure time calculation. The input values are discussed below:

Early Life

Three parameters determine early life failures. The early life probability of occurrence (EP) factor (range of 0 to 1) determines the occurrence of early life failures. Each time an ORU is checked for next failure time, a random number is compared with EP. If the random number is smaller than EP then only the early life weibull distribution is used. Otherwise, the simulation determines the next failure from the random and wearout distributions.

Random & Wearout Events

The MTBF of the ORU determines the next random failure event time while the wearout mean life and shape determines the next wearout failure event time. These two event times are compared. The earliest time is considered the next failure event. The other, later, time is discarded.

K-factors

K factors are a means to account for extra maintenance actions that are not part of the random and wearout failure estimates. The MTBF and mean wearout life are modified by the K-factor as shown in Appendix C. The early life distribution is not affected by the K-factors.

Early Life/Reliability Growth Factors

These factors are used to account for early life and technology improvement of the ORUs. These factors are combined with the K-factor by multiplication and then used to modify the ORU mean life. Three factors with decreasing values are generally used. The first failure time of an ORU during a mission is modified by the first factor. The second failure time by the second factor and the third and subsequent failures by the third factor. This improves the failure rate of the ORU with subsequent replacement. It is based on the assumption that improvements are made in the replacement ORUs that reduce the failure rate of the ORU. While the approach was developed to model early failures it is more useful in accounting for reliability growth.

Replacement Downtime
The simulation uses this value as an average time before a replacement for the failed ORU is delivered to the site and ready for replacement. This time period is added to the MTTR to determine when the new ORU will start operation. Since the simulation only estimates a single ORU, interactive effects from grouping of repairs, and backlogs are not modeled.

4.4 Variable Failure Rates

Both random and wearout failure distributions can be modeled with a time varying mean value. This feature was added to more accurately depict situations where the equipment experiences different environmental/operational conditions. The effect of these varying conditions is usually depicted in a single time-averaged duty cycle factor. In a discrete event simulation, like RENEW, it is possible to represent the timing of the expected conditions and represent the changes in MTBF and mean life as a direct result of the changing conditions.

The data entry consist first of the number of segments, then the MTBF or Mean Life parameter value and the end of the mission based time segment for which this value applies. These values are entered initially through [K]eyboard entry *{Main Menu}* or later using the *List/Change Parameters* menu.

The modeling approach for variable MTBF and variable Mean Life, although similar, are treated differently in the simluation. For random distributions, the algorithm does not have to track the effect of the previous operation because of the "memoryless" characteristic of a random distribution. However, calculations using the wearout distribution require tracking the effect of previous time periods on shortening of the equipment life.

4.4.1 Variable Random Failure Rate

The algorithm is shown in Figure 7. The MTBF for the first time period is determined. The exponential distribution is then used to calculate the time to failure (TTF_i) as shown in Appendix C. This TTF_i plus the offset from the previous period is compared to the next time period, t_{i+1}. If the equipment survives past the next period then another TTF_i is calculated using the next MTBF. This process repeats until a TTF_i is less than the next period, t_{i+1}.

4.4.2 Variable Mean Wearout Life
The Time to Failure algorithm for variable mean life using a Weibull distribution is depicted in Figure 8. This algorithm will calculate a wearout time given a time varying (in segments) mean life.

Failure times are calculated for each segment that take into account the previous wear on the equipment. This "memory" of previous environments is factored into the calculation. First, a single random number is used for all time segments since a single event is being calculated from a composite function of all the wearout distributions across all the time segments of the mission. Second, an offset is calculated to account for the wear in the previous time segments.

The process repeats until the equipment failures before the end of a segment. If the equipment survives into the last segment, it will fail during this segment since the failure time will be less than infinity (inf).

An example of the simulation calculations is shown in Appendix G using the parameters in Figure 8. The given values are a Weibull shape of 3, a single random number of 0.786 for this single time to failure calculation, and an ORU activation at t=0. The given values for variable mean life (μ_i) are shown for each segment (i). For example, mean life is 10 years from the 3rd to 4th year of the mission. The Simulation Example lists the changing parameter values as the loop in Appendix G is executed until the wearout time to fail is determined. Initial values are shown under i=0. The parameter t_b accounts for any delayed activation of the ORU. It is set to zero since the ORU is activated at the start of the mission. R_{end} is 1.0 assuming the ORU is new. For i=1, the mean life, is selected and the characteristic life (θ_i) is calculated from Appendix C equation 1). A time to fail, TTF_i, is calculated solely from the characteristic life and the "single" random number. TTF_i is then adjusted for previous wear using t_s and then to the mission timeline using t_b. The time t_s is calculated using the reliability at the end of the previous segment, R_{end}. The time t_b tracks the end of the last segment in mission time. The resulting TTF_w is then compared to the end of the segment, t_{i+1}. For i=1, Since 4.18 is greater than 3 years, the ORU has survived this segment. An equivalent operating time is calculated for the end of the segment, t_{end}, using the start time offset, t_s, and the segment duration, ($t_{i+1} - t_i$). This time is used to calculate the reliability at the end of this segment, R_{end}. The process repeats with retrieval of the next segment mean life and recalculation of the parameters until a failure time, TTF_w, is less than the end of a time segment. In this example, the ORU survives into the last segment with 5.16 years returned as the wearout failure time.

4.5 K-Factors & Removal Ratios

Experience has shown that the number of maintenance actions are generally higher than the number of confirmed failures [RAMS, 1988, p.102]. These extra maintenance actions include both replacement of ORUs and non-replacement actions (e.g. adjustments, no fault found). To account for this discrepancy, K-factors have been developed to estimate the increased number of maintenance events. An approach for quantifying these values using field data has been developed by the External Maintenance Task Team [EMTT, Vol. I, Pt. 2, Sec. D-2] and re-evaluated by the External Maintenance Solutions Team [EMST]. The K-factors were developed to depict the increased maintenance due to the type of ORU. Six ORU equipment types were defined. These factors translate the MTTF value into a Mean Time Between Maintenance Actions (MTBMA):

$$7) \quad K = \frac{\text{\# Maintenance Actions}}{\text{\# Confirmed Failures}} = \frac{\text{MTTF}}{\text{MTBMA}}$$

LeRC has been using a removal ratio (range of 0 to 1) to adjust the MTBMA for maintenance actions that do not require a spare ORU. This converts the MTBMA to a Mean Replacement Interval (MRI):

$$8) \text{ Removal Ratio} = \frac{\text{\# Replacements}}{\text{\# Maintenance Actions}} = \frac{\text{MTBMA}}{\text{MRI}}$$

4.6 Resource Estimation

Mean maintenance crew-hours/year (MMH/year) and resupply quantity are calculated from the results of the RENEW simulation. The Maintenance Action Rate (MAR) gives the rate of maintenance event occurrence for all ORUs of a particular type.

9)   MAR = # of ORUs * # of failure events/year = 1 / MTBD

The MMH/year is calculated from the Mean Time to Repair (MTTR) and the MAR:

10) MMH/year = MTTR * MAR * # of Crew

An overall Spares Launch Rate (SLR) is calculated from the quantity of ORUs and the MRI:

11) $\quad SLR = \dfrac{\text{\# of ORUs}}{\text{MRI}} = MAR * RR$

The annual resupply mass results from the SLR and mass of an ORU:

12) $\quad$ Resupply Mass/year $=$ ORU Mass $*$ SLR

The process of calculating MMH/year and annual resupply mass using equations 8) to 12) is shown in Figure 9.

4.7 Results

Both average and time-varying results are available from the simulation. The following averages of the simulation are calculated:

MTBD

The Mean Time Between Demand (MTBD) for maintenance is an average derived from the mission time and the total number of ORU maintenance events. It is based on the mission time and not the operating time of the ORU. The MTBD is a composite value that accounts for the total quantity and deployment schedule of a type of ORU on orbit.

MTBM

The Mean Time Between Maintenance (MTBM) is an average of the number of ORU operating hours between maintenance events. This value is for a single ORU.

Percent failure type contribution

The percent of each type of failure (early, random, wearout) is calculated from a tally of the total number of failures and each failure type.

4.8   Assumptions

No prediction is complete without a list of the assumptions used to calculate the results. The following is a summary of the assumptions used by RENEW.

o   Only ORU level items fail and get repaired
o   ORU restored to good-as-new condition
o   An average resupply interval is used for each failure
o   ORU failures can be modeled with the combined Early Life, Random and Weibull distributions
o   There are no interactions between ORUs during maintenance; each ORU is repaired independently
o   Random and wearout events are independent
o   There is no ORU internal redundancy
o   Repair queues are not modeled
o   Downtime effects from shuttle resupply intervals, maintenance backlogs, and grouping of repairs are estimated with a single downtime parameter
o   A sufficient number of trials have been run to give the necessary accuracy
o   K-factor used on both random and wearout
o   K-factors accurately represent increased maintenance for each ORU based on its type
o   The same K-factors apply to both random and wearout events
o   Downtime is a single average value and does not consider:
        On-orbit sparing
        Deferred maintenance
        Variable MTTR
o   The repair ratio is not applied in the simulation
o   K-factors only apply to MTBF and wearout life but not MTBFmmd
o   The system will not be repaired after the end of the defined mission time
o   The results are only as accurate as the assumptions

APPENDIX A - INPUT DATA DESCRIPTIONS

KEYBOARD DATA ENTRY
The following data items are requested during [K]eyboard data input *{Main Menu}*.
The valid input values are shown in parenthesis (). Values may be changed from the
{List/Change Parameters Menu} after keyboard data entry.

ORU Abbreviation/Name
This name may be any length. However, the first 8 characters must be unique since
this is used to create the DOS data file name.

Reliability Type (EL, EC, ST, SM, EM, ME)
This assignment controls which default K-factor is selected for the ORU. The list of
default K-factor values can be viewed and changed from the [C]onstants selection
{Main Menu}. The default K-factor assigned to an ORU may be changed in the
[L]ist/Change Parameters selection *{Main Menu}*.

No. of ORUs (>0)
This indicates the number of ORUs that will be simulated. Start times will be
requested for each of these ORUs.

Early Failure Probability (0 to 1)
This parameter determines the chance of an early failure occurrence. The early
failure model is removed from the simulation if this parameter is set to 0.

Mean Early Life (>0)
This parameter is used if the probability of early failure is not 0. The early failure
model is a Weibull distribution with a decreasing hazard rate (shape < 1). This value
sets the mean life of the model.

Early Life Weibull Shape (0 to 1)
This parameter is used if the probability of early failure is not 0. The shape must be
less than 1 since the early failure model must have a decreasing hazard rate.

MTBF Type (V, C)
This selection determines whether there is a single (C-Constant) or multiple (V-
Variable) MTBF values over the mission time.

Number of MTBF Periods
This appears if a variable MTBF Type is selected. The value indicates how many MTBF values will be modeled over the mission time.

MTBF (>0)
The Mean Time Between Failures (MTBF) represents the chance of random failure during the mission.

Duty Cycle (0 to 1)
This factor is directly applied to the MTBF to account for the ratio of ORU operating time to total time. Non-operating time is assumed to have an infinite MTBF.

MTBF-Micrometeroid/Debris (>0)
This parameter accounts for the random occurrence of a failure caused by a micrometeroid or debris strike. This is separated from the MTBF for tracking proposes and other factor application. The K-factor and duty cycle is applied to the MTBF first. The result is then combined with the MTBF-Micrometeroid/Debris for determination of event times. Set this value to 1E+29 to remove it from the simulation.

Wearout Mean Life Type (V, C)
This selection determines whether there is a single (C-Constant) or multiple (V-Variable) Wearout Mean Life values over the mission time. The Weibull Failure Free Period is set to 0 when variable mean life is used. A single Weibull Shape Factor is applied to the mean life in all time segments.

Number of Mean Life Periods
This appears if a variable Mean Life Type is selected. The value indicates how many mean life values will be modeled over the mission time.

Wearout Weibull Mean Life (>0)
This is the mean life, μ, of the Weibull wearout distribution. The mean life parameter is converted to characteristic life for time to failure calculations. See Appendix C, equation 1).

Wearout Weibull Failure Free Period (>=0)
This is the time period over which no wearout failures can occur. It is the location parameter of the Weibull distribution, γ.

Wearout Weibull Shape Factor (>1)
This is the shape parameter, β, of the Weibull wearout distribution.

Replacement Downtime (>=0)

This parameter is the average time to obtain a replacement ORU. It is used to sumulate the logistics delay time. The total downtime is the sum of this parameter and the MTTR for the ORU.

Mission Time (>0)

This is set to the length of one mission in years. Failures will be repeatedly simulated up to this end of mission time.

No. Divisions/year (>=1)

This sets the number of event divisions per year for collection of histogram data. More simulations are needed to obtain good data as the number of divisions are increased. It is usually set to 1 for collection of failures over one year intervals. A value of 4 would collect failures over 3 month intervals.

Number of Simulations (>=1)

This is the number of simulations of each mission time that will be performed by RENEW. At least 100 simulations should be run to in order to depict the maintenance event pattern.

Replacement Ratio (0 to 1)

This is an average value representing the percentage of times that an ORU will be replaced once a failure event occurs. A value of 1 means that a replacement spare will be required for all failures. A value of 0 means failures are repaired without the need for a spare. This difference is reflected in the downtime and failure/replacement event calculations.

ORU Start Times (>=0)

This is the start time, using the mission time clock, for each ORU. This allows for staged deployment. A value of 5 indicates that the ORU is not present until 5 years into the mission. To depict standby failures before activation, the variable MTBF or variable life parameters should be used.

APPENDIX B - PROGRAM INSTALLATION AND DATA FILES

PROGRAM INSTALLATION

There is only a single program file that is needed to run RENEW. The file "RENEW32.EXE" should be copied to the directory where the data files will be stored. The program can be run from a floppy or hard disk system. To run the program, type "RENEW32" from the DOS prompt. The main menu screen will be displayed. A sample set of data and results files is provided on the disk with the base file name "ORU".

DATA FILES
The following data files are generated by RENEW:

File
Extension Description
.RD3   ORU Data File
           This is the basic ORU data file. It contains both input data as well as
           results. Combining both input and results ensures traceability of results to
           input data. The file may contain only input data if the simulation was not
           executed when the data was saved. Once results have been generated,
           this file will contain the input data followed by the results.

.RB3   Batch file
           This is and ASCII file that contains a listing of individual ORU file names.
           The file names, with the .RD3 file extension, are left justified with no drive
           or directory attached. RENEW will only use files in the current default
           directory.

.RS3   RENEW Summary File
           This is an 80 column report of selected input data and results. This is
           generated from the *Batch And Summary Files Menu*.

.RE3   RENEW SE-03 report
           This report is a 132 character wide report of selected input data and
           results. It is generated from the *Batch And Summary Files Menu*.

APPENDIX C - EQUATIONS USED IN RENEW

Characteristic Life (θ) is calculated from the Mean Life (μ), Failure Free period (γ) and Shape (β) using the gamma function [Lewis, p. 97]:

1)
$$\theta = \frac{\mu - \gamma}{\Gamma [1 + (1/\beta)]}$$

Early life failures are modeled using a weibull distribution with a mean life (μ_e) a shape factor (β_e) less than 1, and a random number (R) substituted for the Reliability to obtain the time to fail (TTF_e):

2)
$$TTF_e = \frac{\mu_e}{\Gamma [1 + (1/\beta_e)]} [-\ln(R)]^{(1/\beta_e)}$$

For the wearout distributions, the K-factor is applied as a multiplier to the hazard rate, h(t). An effective characteristic life (θ') with K-factor effects is calculated:

3)
$$h(t) = \frac{K \, \beta \, t^{\beta-1}}{\theta^\beta} = \frac{\beta \, t^{\beta-1}}{(\theta')^\beta}$$

4) where,
$$\theta' = \frac{\theta}{K^{(1/\beta)}}$$

A Time To Failure (TTF_w) for the weibull wearout distribution is calculated from the Characteristic Life (θ), K-Factor (K), and Shape (β):

5)
$$TTF_w = \frac{\theta}{K^{(1/\beta)}} [-\ln(R)]^{(1/\beta)}$$

6)
$$TTF_w = \frac{\mu}{\Gamma [1 + (1/\beta)] K^{(1/\beta)}} [-\ln(R)]^{(1/\beta)}$$

A Time To Failure for the exponential (TTF_r) distribution is calculated from the MTBF, K-factor (K) and a random number (R) substituted for the reliability:

7)
$$TTF_r = - \ln(R) * \frac{MTBF}{K}$$

APPENDIX D - ABBREVIATIONS AND SYMBOLS

Abbreviations/Acronyms

CFD	Cumulative Frequency Distribution
DOS	Disk Operating System
EVA	Extravehicular Activity
IVA	Intravehicular Activity
LeRC	NASA Lewis Research Center
LDT	Logistics Downtime
MAR	Maintenance Action Rate
MMD	Micrometeroid Debris
MRI	Mean Replacement Interval
MTBF	Mean Time Between Failure
MTBFE	Mean Time Between Failure Event
MTBD	Mean Time Between Demand
MTBMA	Mean Time Between Maintenance Action
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
ORU	Orbital Replacement Unit
pdf	Probability Density Function
POS	Probability of Sufficiency
ROB	Robotic
RR	Removal Ratio
R&M	Reliabillity & Maintainability
SLR	Spares Launch Rate
SSFP	Space Station Freedom Program
TTF	Time To Failure
WP-04	Work Package 4, Space Station Freedom Program

Symbols

β	Weibull shape parameter (beta)
$\Gamma(x)$	Gamma function
γ	Weibull failure free period
$h(t)$	Hazard rate function
λ	Failure rate
μ	Mean life
$R(t)$	Reliability function
θ	Weibull characteristic life

APPENDIX E - BIBLIOGRAPHY

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APPENDIX F - SAMPLE RENEW DATA FILE

<u>DATA FILE: ORU1.RD3</u>

```
Renewal Simulation_V                        3.2
Simulation_Run_Date                         10-27-1992
ORU_Name                                    ORU_1
ORU_Type                                    EL
No._of_ORUs                                 6
Prob._of_Early_Failure                      .05
Early_Mean_Life_(years)                     1
Early_Shape                                 .4
Variable/Constant MTBF                      C
MTBF_(years)                                35
MTBF_Micrometeroid_(years)                  1E+29
Variable/Constant Life                      C
Wearout_Mean_Life_(years)                   15
Wearout_Failure_Free_Period_(years)         0
Wearout_Shape                               10
Replacement_Downtime_(years)                0
Number_of_Simulations                       1000
Mission_Time_(years)                        30
Bins_per_year                               1
Rel_Growth_Factor_1                         3.3
Rel_Growth_Factor_2                         2.17
Rel_Growth_Factor_3                         .6666667
K-factor                                    1.63
ORU_Mass                                    30
EVA_MTTR                                     .6
Robotic_MTTR                                0
IVA_MTTR                                     0
Replacement_Ratio                           .8
No._EVA_Crew                                1
No._IVA_Crew                                0
Null_Data                                   1
Null_Data                                   1
ORU_#                                       Start_Time_year
  1                                         0
  2                                         0
  3                                         1.5
  4                                         1.5
  5                                         4
  6                                         4
Total_Failures/Mission                      17.911
Std_Dev                                     2.227564
Average_Failures/year                       .5970333
Max_Failures_year                           5
Max_No._Failures                            .861
Percent_Early                               6.214058
Percent_Random                              67.98057
Percent_Wearout                             25.80537
Total_No._Maintenance_Actions               17.911
Total_No._Replacements                      14.353
Std_Dev                                     2.443022
Total_Available_Time                        169
Total_Downtime_(years)                      1.226781E-03
MTBFE_(years)                               1.674948
ORU_MTBFE_(years)                           9.435474
Mean_Annual_Resupply_Mass_(lbs)             14.3288
EVA_MMH/yr                                   .35822
Robotic_MMH/yr                              0
IVA_MMH/yr                                   0
```

Time	#_Failures	#_Early	#_Random	#_Wearout
1	.368	.08	.288	0
2	.506	.088	.418	0
3	.551	.04	.511	0
4	.564	.029	.535	0
5	.861	.103	.758	0
6	.727	.035	.691	.001
7	.728	.047	.681	0
8	.684	.04	.643	.001
9	.691	.05	.639	.002
10	.571	.02	.539	.012
11	.564	.028	.523	.013
12	.614	.027	.551	.036
13	.623	.033	.515	.075
14	.639	.028	.484	.127
15	.633	.032	.438	.163
16	.66	.028	.4	.232
17	.628	.026	.338	.264
18	.62	.04	.336	.244
19	.644	.036	.287	.321
20	.639	.035	.305	.299
21	.585	.035	.27	.28
22	.564	.032	.261	.271
23	.545	.025	.266	.254
24	.578	.03	.253	.295
25	.532	.029	.228	.275
26	.532	.026	.249	.257
27	.478	.025	.194	.259
28	.545	.024	.21	.311
29	.507	.024	.178	.305
30	.53	.018	.187	.325

Min_Failure_Events	11
Max_Failure_Events	26
Min_Replacement_Events	6
Max_Replacement_Events	22

Failure_Occurrence_Histogram

11	2	0.0020
12	2	0.0040
13	13	0.0170
14	42	0.0590
15	66	0.1250
16	141	0.2660
17	173	0.4390
18	185	0.6240
19	157	0.7810
20	90	0.8710
21	65	0.9360
22	39	0.9750
23	17	0.9920
24	7	0.9990
25	0	0.9990
26	1	1.0000

Replacement_Occurrence_Histogram

6	1	0.0010
7	4	0.0050
8	3	0.0080
9	11	0.0190
10	31	0.0500
11	59	0.1090
12	123	0.2320
13	140	0.3720
14	155	0.5270
15	156	0.6830
16	126	0.8090
17	98	0.9070
18	47	0.9540

```
  19                       27          0.9810
  20                       10          0.9910
  21                        8          0.9990
  22                        1          1.0000
Year_by_Year_Histogram_Data
Max_Failure_Occurrences              386
Max_Failure_Events           5
Max_Replacement_Occurrences          375
Max_Replacement_Events       5
Year 1  Failures
  684            268          44           4            0            0
Year 1  Replacements
  737            236          25           2            0            0
Year 2  Failures
  602            304          83           9            1            1
Year 2  Replacements
  668            271          54           6            1            0
Year 3  Failures
  577            315          90          16            2            0
Year 3  Replacements
  643            279          67           9            2            0
Year 4  Failures
  577            306          95          20            2            0
Year 4  Replacements
  635            291          66           8            0            0
Year 5  Failures
  405            386         161          39            9            0
Year 5  Replacements
  482            375         112          28            3            0
Year 6  Failures
  490            352         112          36            7            3
Year 6  Replacements
  562            324          93          16            2            3
Year 7  Failures
  477            364         123          28            6            2
Year 7  Replacements
  542            341          91          20            5            1
Year 8  Failures
  508            342         117          24            9            0
Year 8  Replacements
  577            316          88          18            1            0
Year 9  Failures
  503            343         122          24            8            0
Year 9  Replacements
  569            332          83          14            2            0
Year 10  Failures
  577            303          96          21            2            1
Year 10  Replacements
  640            270          75          12            2            1
Year 11  Failures
  578            305          96          17            4            0
Year 11  Replacements
  659            264          64           9            4            0
Year 12  Failures
  543            329         103          21            4            0
Year 12  Replacements
  625            287          73          13            2            0
Year 13  Failures
  546            320         109          18            4            3
Year 13  Replacements
  615            294          75          13            3            0
Year 14  Failures
  529            344          92          31            2            2
Year 14  Replacements
  602            306          73          18            1            0
Year 15  Failures
```

547	313	108	25	6	1
Year 15 Replacements					
607	288	90	13	2	0
Year 16 Failures					
498	370	109	20	3	0
Year 16 Replacements					
572	337	77	12	2	0
Year 17 Failures					
526	348	100	24	2	0
Year 17 Replacements					
603	317	71	9	0	0
Year 18 Failures					
541	332	100	21	5	1
Year 18 Replacements					
601	308	71	16	3	1
Year 19 Failures					
520	353	98	21	8	0
Year 19 Replacements					
590	314	83	9	4	0
Year 20 Failures					
527	335	111	26	1	0
Year 20 Replacements					
607	297	80	16	0	0
Year 21 Failures					
570	304	101	21	4	0
Year 21 Replacements					
635	274	79	9	3	0
Year 22 Failures					
558	335	93	13	1	0
Year 22 Replacements					
625	303	65	7	0	0
Year 23 Failures					
581	314	86	17	2	0
Year 23 Replacements					
645	289	55	10	1	0
Year 24 Failures					
576	301	98	20	4	1
Year 24 Replacements					
642	268	74	14	2	0
Year 25 Failures					
587	313	86	10	3	1
Year 25 Replacements					
643	291	58	7	0	1
Year 26 Failures					
590	317	69	20	3	1
Year 26 Replacements					
664	275	47	11	3	0
Year 27 Failures					
622	294	71	10	3	0
Year 27 Replacements					
694	250	48	8	0	0
Year 28 Failures					
575	329	76	16	4	0
Year 28 Replacements					
650	281	57	10	2	0
Year 29 Failures					
594	317	79	9	0	1
Year 29 Replacements					
657	278	60	5	0	0
Year 30 Failures					
591	304	92	10	3	0
Year 30 Replacements					
657	270	63	8	2	0

APPENDIX G - VARIABLE MEAN LIFE EXAMPLE

Given Values:

Mean Life Weibull Shape (β) = 3
Random number (RND#) = .786
Start Time = 0

Variable Mean Life Data (years):

Segment (i)	From	To	Mean Life
1	0	3	6
2	3	4	10
3	4	inf	12

Simulation Example (refer to Figure 8):

Parameter	Values			
i	0	1	2	3
μ_i	--	6	10	12
θ_i	--	6.72	11.2	13.4
TTF_i	--	4.18	6.97	8.36
t_s	--	0	5	7.2
TTF_w	--	4.18	4.97	5.16
t_{i+1}	--	3	4	inf
t_i	--	0	3	--
t_{end}	--	3	6	--
t_b	0	3	4	--
R_{end}	1.0	.915	.857	--

FIGURE 1 - Data Entry/Retrieval Process

```
┌──────────┐        ┌──────────┐      ┌──────────┐      ┌──────────┐
│[K]eyboard│        │  Input   │      │[E]xecute │      │Input Data│
│Data      │ ─────▶ │  Data    │ ───▶ │Simulation│ ───▶ │    &     │
│Entry     │        │          │      │          │      │ Results  │
└──────────┘        └────┬─────┘      └──────────┘      └────┬─────┘
                         │ ▲                                 │ ▲
                         ▼ │                                 ▼ │
              ┌────────────────────┐          ┌──────────────────────────────┐
              │[F]ile Data Input   │          │[F]ile Data & Results Input    │
              │[S]ave Input Data   │          │[S]ave Input Data & Results    │
              └─────────┬──────────┘          └──────────────┬───────────────┘
                        │ ▲                                  │ ▲
                        ▼ │                                  ▼ │
        ┌───────────────────────────────────────────────────────────────┐
        │              DOS Data File (.RD3)                              │
        │- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - │
        │                           :                                    │
        │       Input Data          :          Results Data             │
        │                           :                                    │
        └───────────────────────────────────────────────────────────────┘
```
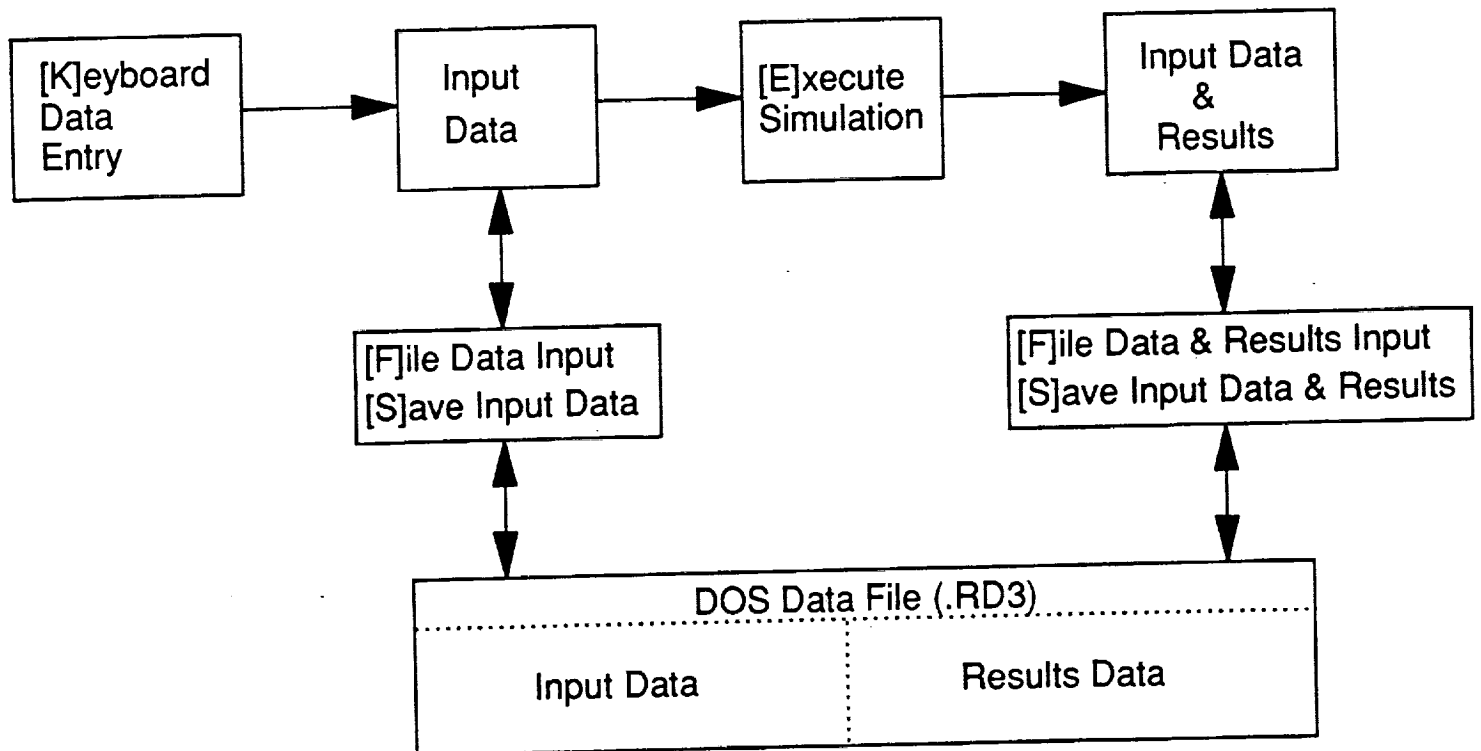
Note: [x] = Selection from Main Menu

FIGURE 2 - Composite Reliability Function Display

Renewal Simulation - V3.2 - Reliability Function - R(t)

Reliability   ORU_1

Early Life Distribution (blue)   Wearout Distribution (red)
  Mean Life: 1 years   Mean Life: 15   years
  Shape: .4   Fail Free: 8   years
  Prob. of Occurrence: 5.00%   Shape: 18
Random Distribution (green)   K-Factor: 1.63
  MTBF: 21.47239 years   Sum of curves (magenta)

Vertical Scale Factor = 1 , Enter new value, or *-Print, <Enter>-Quit: *
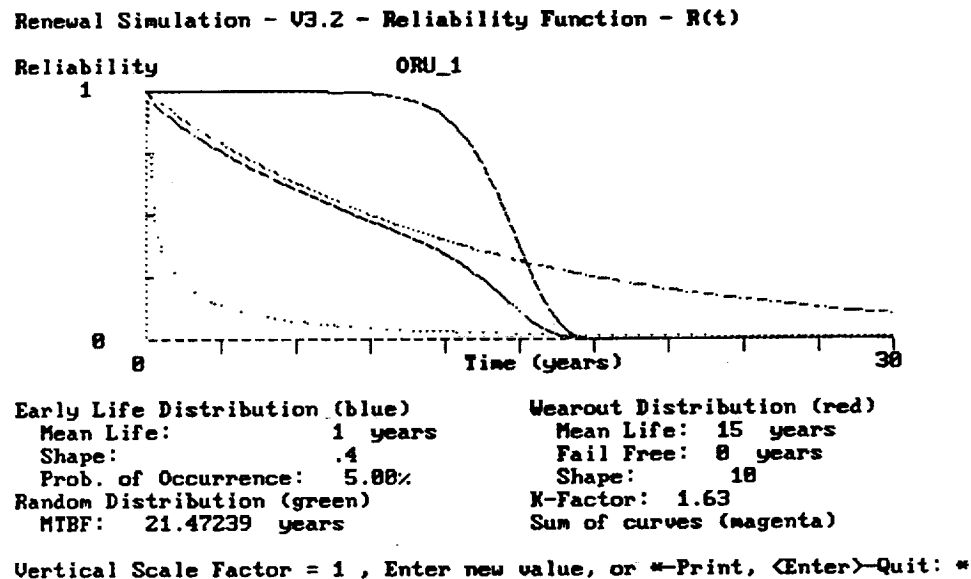
FIGURE 3 - Failure Event Histogram Plot

Renewal Simulation - V3.2 - Event Histogram

No. of Events   ORU_1
  .861

Total Events/Mission: 17.911   Avg. Events/year: .5978333
      6.2% Early   MTBFE: 1.674948 years
     68.8% Random   ORU MTBFE: 9.435474 years
     25.8% Wearout
Max. Events/year: .861   Legend: Total-yellow
Time of Max. Events: 5 years   Random-blue

Plot: E-Early, R-Random, W-Wearout events, <Enter>-Quit, *-Plot: ? *
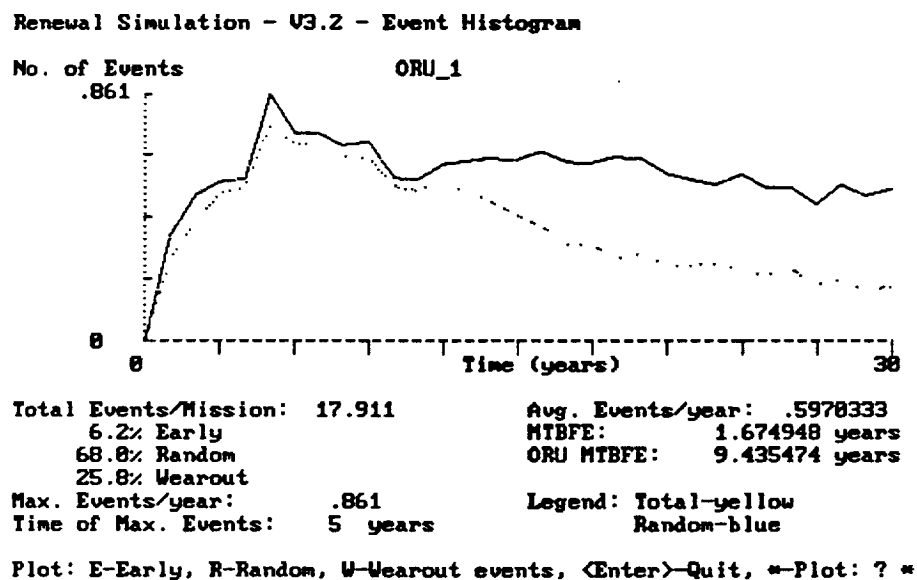
FIGURE 4 - Failure Occurrence Histogram

Renewal Simulation - V3.2 - Failure Occurrence Histogram
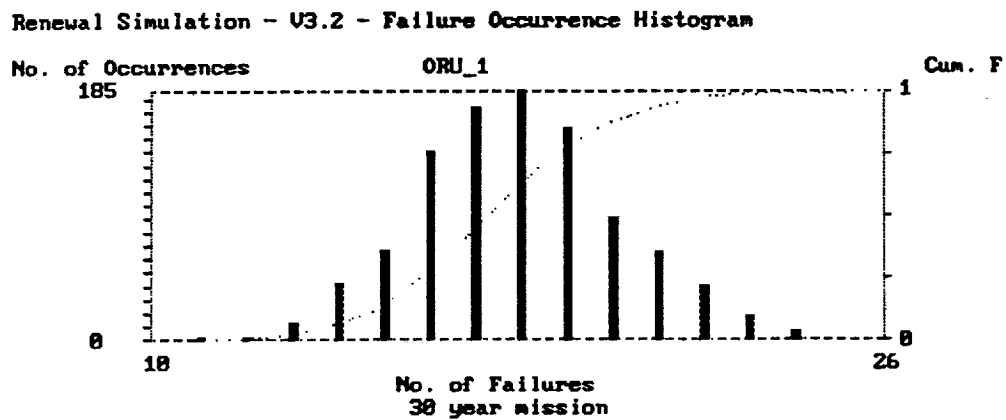
Legend:
  Blue   - Cumulative Frequency Distribution
  Yellow - Number of Occurrences

Enter Year (1.00 incr.), 0-Entire Mission, <Enter>-Next, *-Print, Q-Quit: *
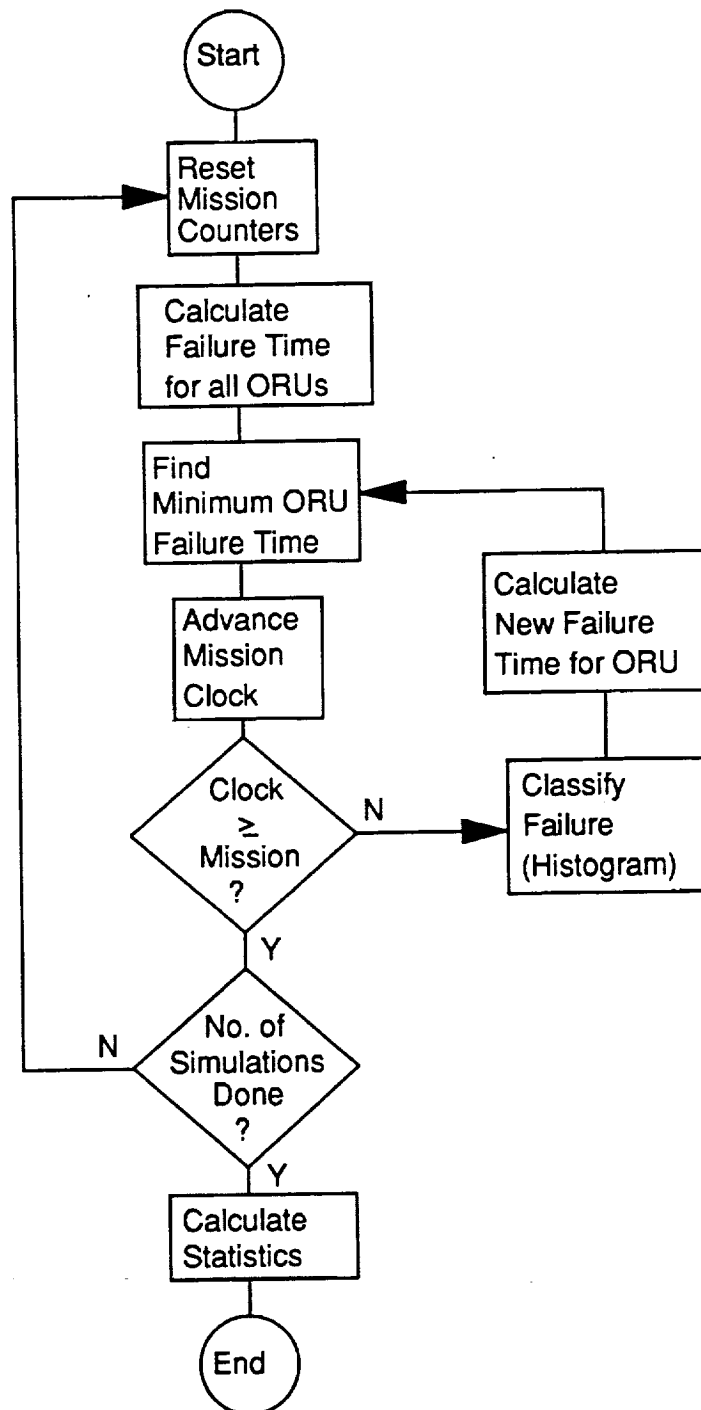
FIGURE 5 - Main Simulation Loop Flow Diagram

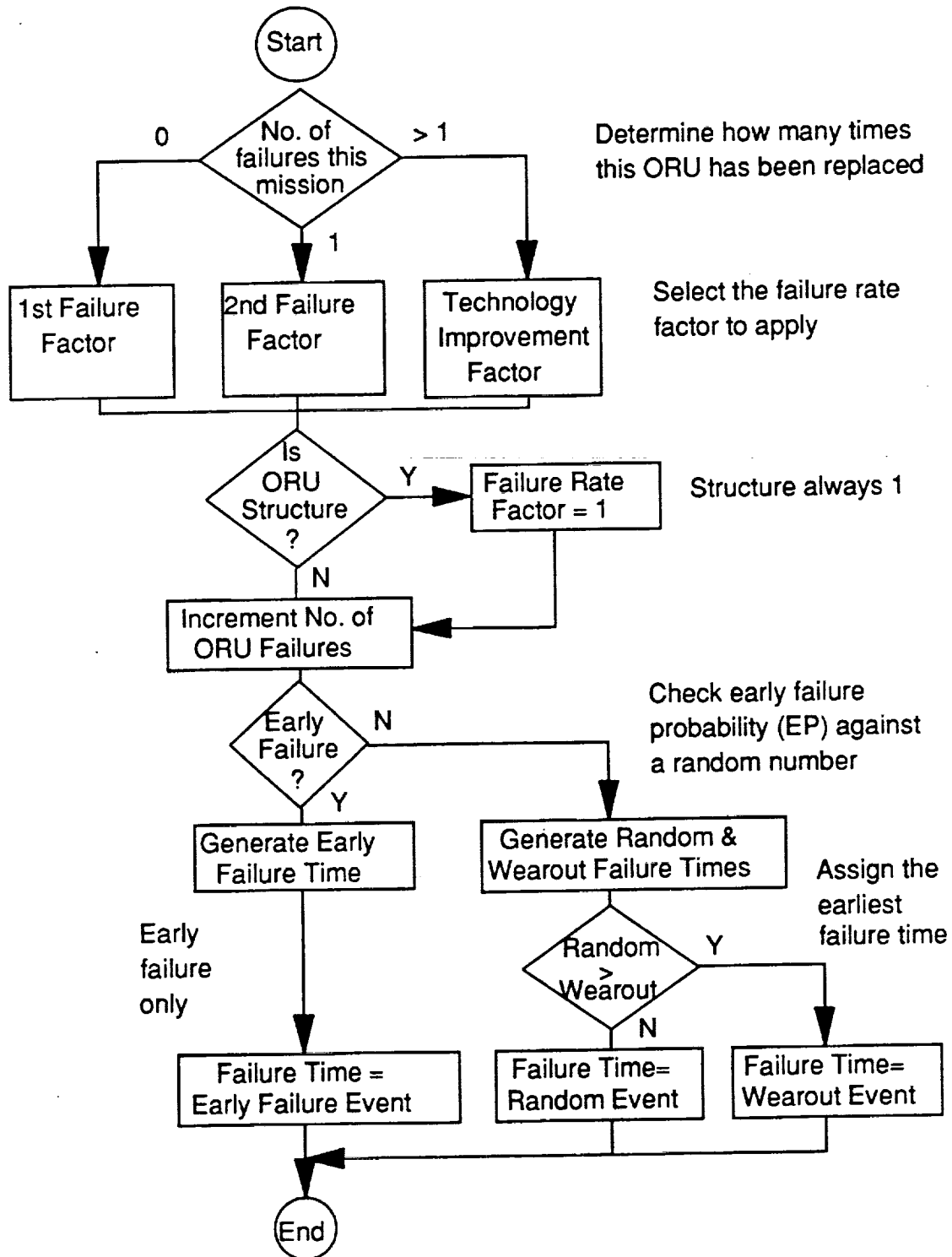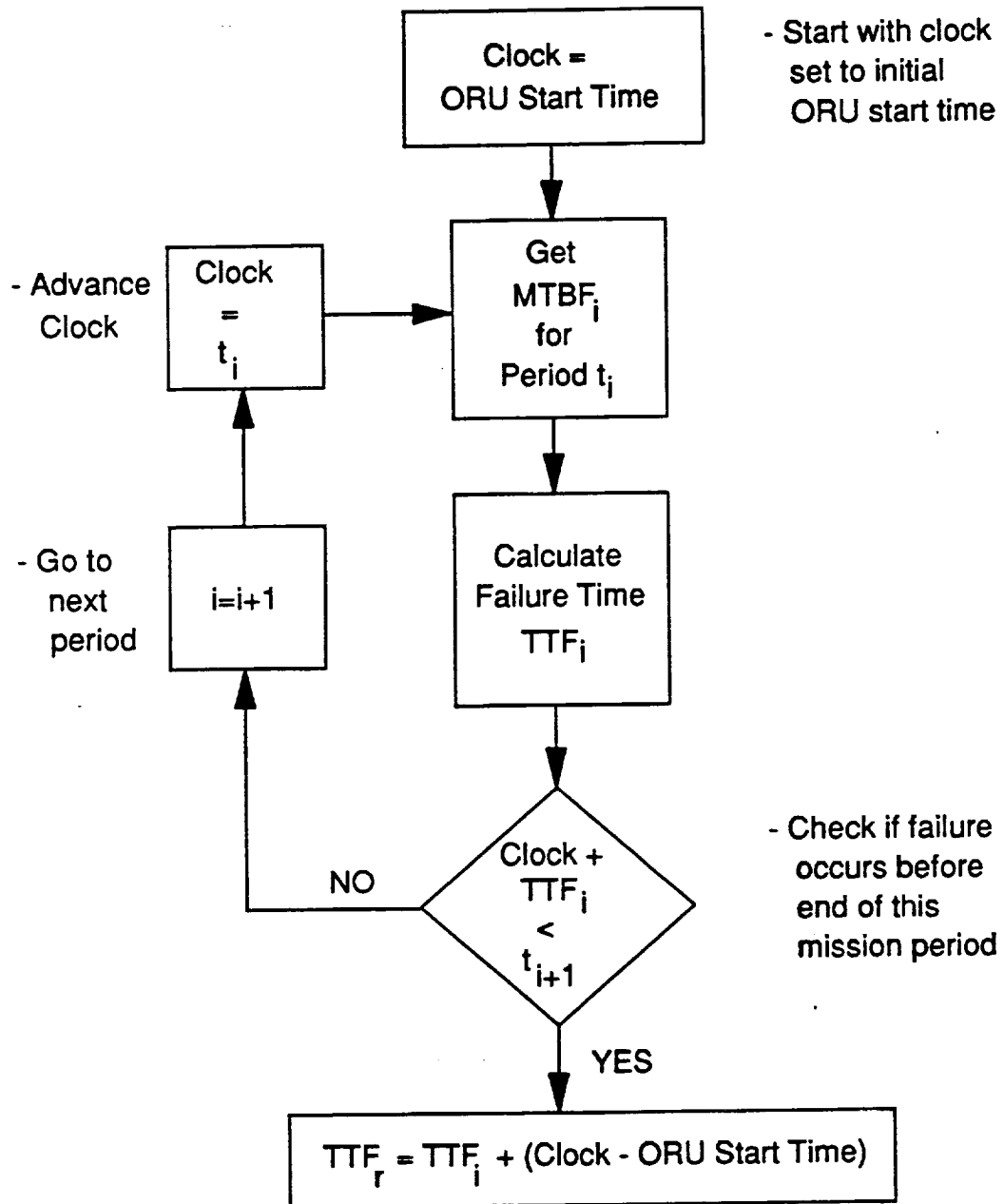## FIGURE 6 - Failure Time Calculation

FIGURE 7 - Variable MTBF Flow Diagram

```
                              ┌─────────────────┐
                              │    Clock =      │      - Start with clock
                              │  ORU Start Time │        set to initial
                              └─────────────────┘        ORU start time
                                       │
                                       ▼
              ┌──────────┐    ┌─────────────────┐
- Advance     │  Clock   │    │      Get        │
  Clock       │    =     │───▶│    MTBF_i       │
              │   t_i    │    │      for        │
              └──────────┘    │   Period t_i    │
                   ▲          └─────────────────┘
                   │                   │
                   │                   ▼
- Go to     ┌──────────┐    ┌─────────────────┐
  next      │  i=i+1   │    │   Calculate     │
  period    └──────────┘    │  Failure Time   │
                   ▲         │     TTF_i       │
                   │         └─────────────────┘
                   │                   │
                   │                   ▼
                   │              ╱─────────╲
                   │             ╱  Clock +  ╲
              NO   │            ╱    TTF_i    ╲    - Check if failure
          ────────┘            ╲     <       ╱      occurs before
                                ╲   t_{i+1}  ╱       end of this
                                 ╲─────────╱         mission period
                                      │
                                      ▼ YES
              ┌──────────────────────────────────────────────┐
              │  TTF_r = TTF_i + (Clock - ORU Start Time)     │
              └──────────────────────────────────────────────┘
```

TTF_i = Time to Fail using $MTBF_i$

TTF_r = Time to Fail, random, for simulation
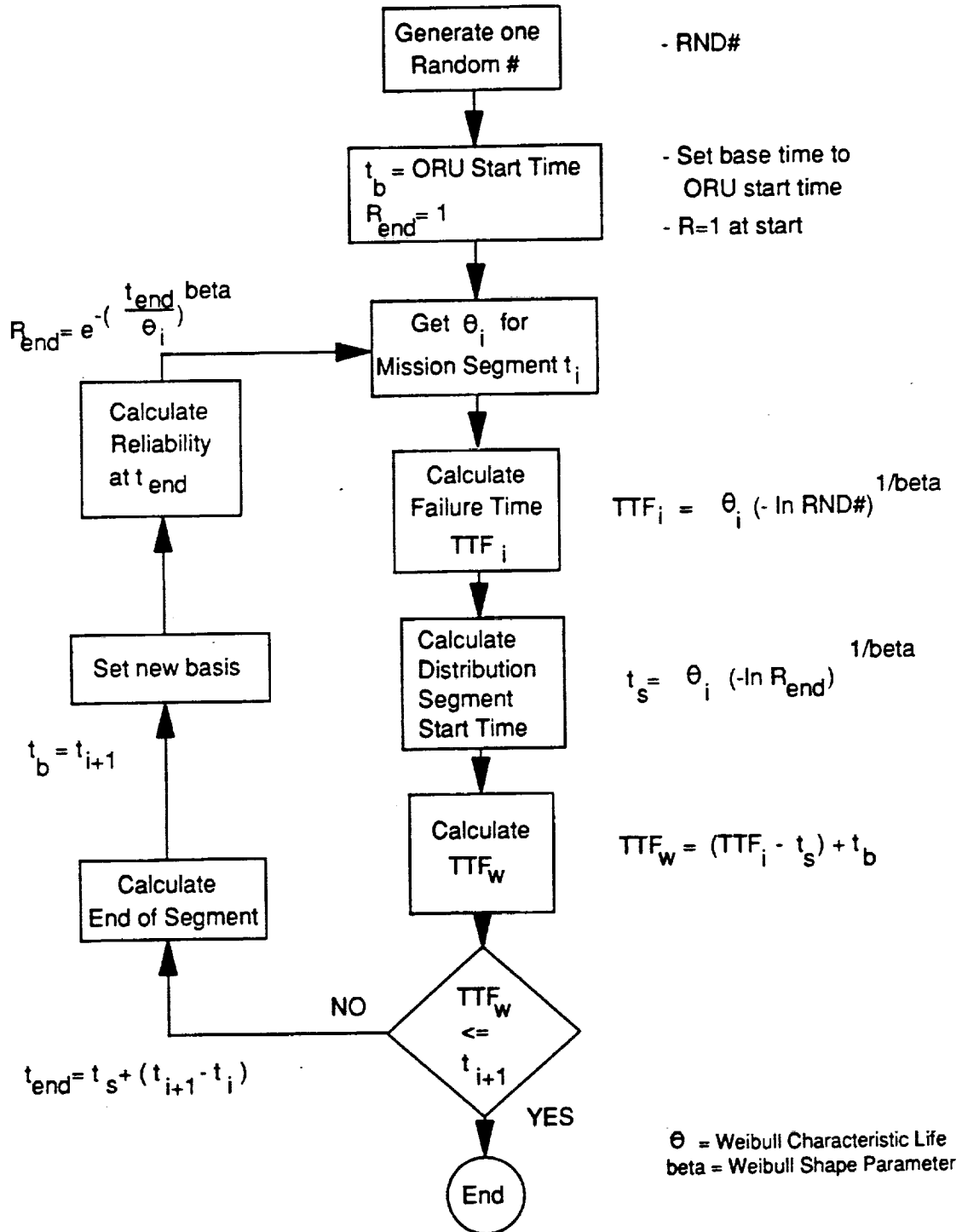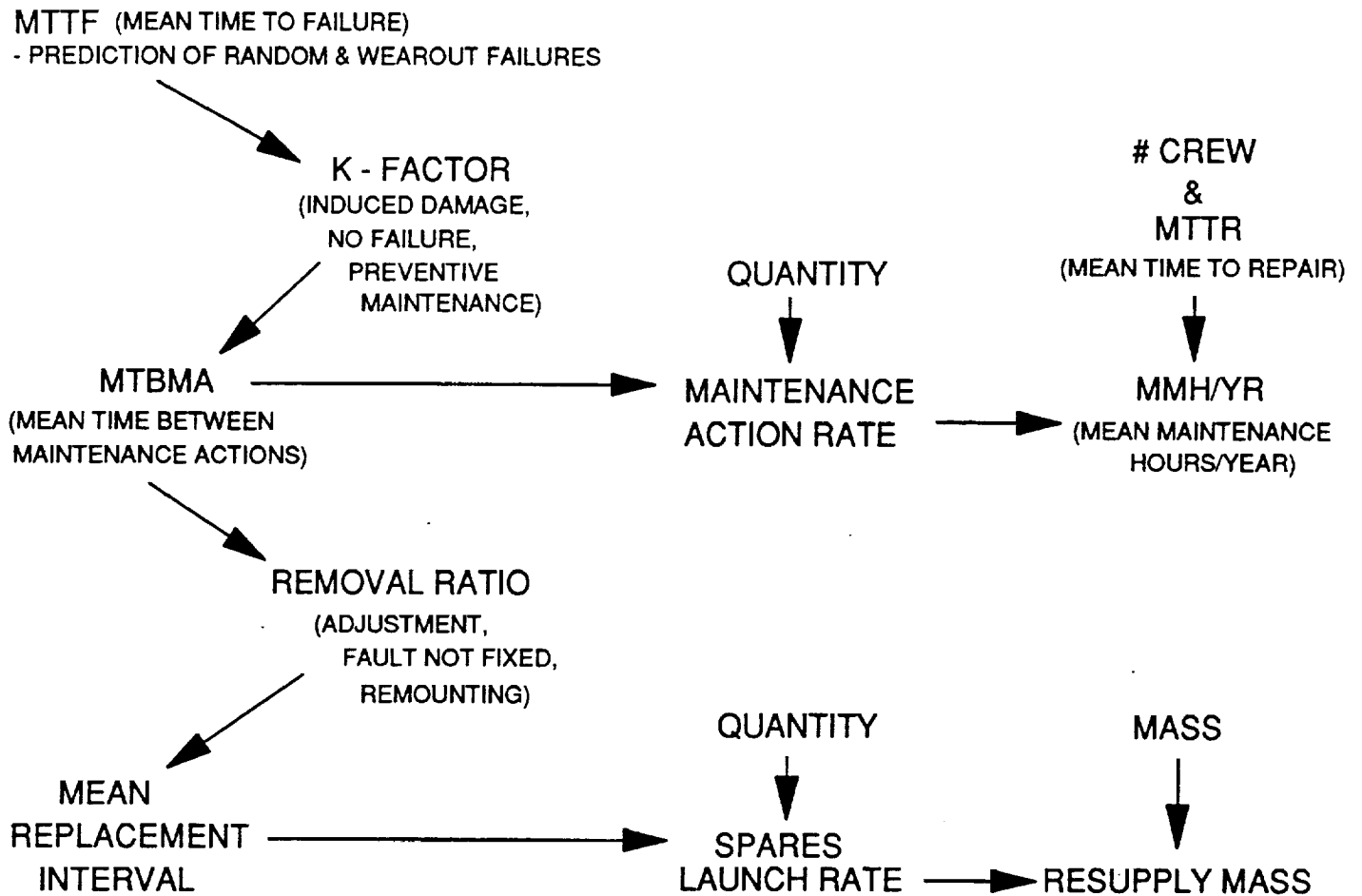
FIGURE 8 - Variable Mean Life Flow Diagram

$R_{end} = e^{-\left(\frac{t_{end}}{\theta_i}\right)^{beta}}$

Generate one Random # — RND#

t_b = ORU Start Time
$R_{end} = 1$

- Set base time to ORU start time
- R=1 at start

Get θ_i for Mission Segment t_i

Calculate Reliability at t_{end}

Calculate Failure Time TTF_i

$TTF_i = \theta_i(-\ln RND\#)^{1/beta}$

Set new basis

$t_b = t_{i+1}$

Calculate Distribution Segment Start Time

$t_s = \theta_i(-\ln R_{end})^{1/beta}$

Calculate End of Segment

Calculate TTF_w

$TTF_w = (TTF_i - t_s) + t_b$

$t_{end} = t_s + (t_{i+1} - t_i)$

NO

$TTF_w <= t_{i+1}$

YES

End

θ = Weibull Characteristic Life
beta = Weibull Shape Parameter

FIGURE 9 - MMH/Year and Resupply Mass Calculations

MTTF (MEAN TIME TO FAILURE)
- PREDICTION OF RANDOM & WEAROUT FAILURES

K - FACTOR
(INDUCED DAMAGE,
NO FAILURE,
PREVENTIVE
MAINTENANCE)

CREW
&
MTTR
(MEAN TIME TO REPAIR)

QUANTITY

MTBMA
(MEAN TIME BETWEEN
MAINTENANCE ACTIONS)

MAINTENANCE
ACTION RATE

MMH/YR
(MEAN MAINTENANCE
HOURS/YEAR)

REMOVAL RATIO
(ADJUSTMENT,
FAULT NOT FIXED,
REMOUNTING)

QUANTITY

MASS

MEAN
REPLACEMENT
INTERVAL

SPARES
LAUNCH RATE

RESUPPLY MASS

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13. ABSTRACT (Maximum 200 words)

RENEW is a maintenance event estimation simulation program developed in support of the Space Station Freedom Program (SSFP). This simulation uses reliability and maintainability (R&M) and logistics data to estimate both average and time dependent maintenance demands. The simulation uses Monte Carlo techniques to generate failure and repair times as a function of the R&M and logistics parameters. The estimates are generated for a single type of orbital replacement unit (ORU). The simulation has been in use by the SSFP Work Package 4 prime contractor, Rocketdyne, since January 1991. The RENEW simulation gives closer estimates of performance since it uses a time-dependent approach and depicts more factors affecting ORU failure and repair than stead-state average calculations. RENEW gives both average and time dependent demand values. Graphs of failures over the mission period and yearly failure occurrences are generated. The averages demand rate for the ORU over the mission period is also calculated. While RENEW displays the results in graphs, the results are also available in a data file for further use by spread-sheets or other programs. The process of using RENEW starts with keyboard entry of the R&M and operational data. Once entered, the data may be saved in a data file for later retrieval. The parameters may be viewed and changed after entry using RENEW. The simulation program runs the number of Monte Carlo simulations requested by the operator. Plots and tables of the results can be viewed on the screen or sent to a printer. The results of the simulation are saved along with the input data. Help screens are provided with each menu and data entry screen.

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